APPARATUS COMPRISING A ROTARY-ACTING PILOT VALVE

Field of the Invention

[0001] The present invention relates generally to valves.

Background

[0002] Solid-fuel gas generators are often used in missiles and rockets to produce hot, high-pressure gas to use as propellant. In some systems, the hot gas is fed to a secondary combustor where it mixes within an in-flowing oxidant, such as air. The gas burns in the secondary combustor and is then exhausted from a thrust nozzle. In some other systems, a secondary combustor is not present; the gas generated by the solid-fuel gas generator is simply delivered to and exhausted from the thrust nozzle.

[0003] It is often necessary to vary a missile's attitude and speed during flight. For missiles that are powered by solid-fuel gas generators, this requires regulating the gas flow during flight, since the gas-generating reaction is uncontrolled. The gas flow can be regulated using a hot-gas control valve.

[0004] In some propulsion systems, the hot-gas control valve is positioned to regulate the flow of gas into the combustor. In some other systems, the control valve is positioned to regulate the flow of gas to the thrust nozzle. In yet some other systems, control valves regulate gas flow to both the combustor and the nozzle.

[0005] FIGs. 1A and 1B depict a simplified schematic of a conventional solid-fuel-sourced propulsion system that includes solid-fuel gas generator **99** for generating propulsion gas **100** and two-stage hot-gas control valve **108** for regulating the flow of gas **100** to thrust nozzle **102**. A two-stage valve is often used for this service (as opposed to a single-stage valve) as a way to reduce valve-actuator power requirements or improve valve response time. FIG. 1A depicts two-stage valve **108** in a "closed" state, wherein gas **100** is prevented from entering mouth **104** of nozzle **102**. FIG. 1B depicts valve **108** in an "open" state, wherein gas **100** is permitted to enter mouth **104** of nozzle **102**.

[0006] Two-stage control valve **108** includes "first stage" or "pilot valve" **110** and "second stage" or "main-stage valve" **112**. The structure of pilot valve **110** is not depicted in FIGs. 1A and 1B; pilot valve **110** is typically one of several known valve

types, such as a flapper valve, spool valve or the like. In the illustration, second stage **112** is a linearly-acting, piston-in-bore arrangement.

[0007] Regardless of its particular configuration, pilot valve **110** actuates second stage **112** of the two-stage valve **108** depicted in FIGs. 1A and 1B. In the state depicted in FIG. 1A, pilot valve **110** causes piston **114** to move "upwards" in bore **116**, sealing mouth **104** of nozzle **102**. This prevents gas **100** in conduit **106** from entering nozzle **102**. In the state depicted in FIG. 1B, pilot valve **110** causes piston **114** to move "downwards" in bore **116**, such that mouth **104** of nozzle **102** is open. In this state, gas **100** flows into nozzle **102**. Piston **114** can actuated pneumatically, electromechanically, or via other modalities.

[0008] As conventionally implemented, pilot valve **110** must overcome certain forces to operate. For example, if pilot valve **110** is a flapper valve, the valve element (*i.e.*, the "flapper,") must typically "lift" against a pressure load. And while some valves are statically pressure balanced, they are usually not dynamically pressure balanced. When used for aeronautical applications, such as in a missile, most conventional implementations of pilot valve **110** must also contend with g-forces.

[0009] Overcoming these loads necessitates an increase in the power required for actuation relative to what would otherwise be necessary. Consequently, it would be desirable to provide a valve (*e.g.*, a pilot valve for a two-stage, hot-gas control valve, *etc.*) that is configured such that it does not lift against a pressure load, is substantially insensitive to g-loads, and is immune from pressure imbalances.

Summary

[0010] The illustrative embodiment of the present invention is a propulsion system that incorporates a rotary-acting pilot valve that avoids some of the disadvantages of the prior art. In the illustrative embodiment, the rotary-acting pilot valve functions as the first stage of a two-stage, hot-gas control valve that regulates a flow of gas propellant to a thrust nozzle.

[0011] In accordance with the illustrative embodiment, the rotary-acting pilot valve comprises a rotor that resides in a chamber. The rotor is supported within the chamber in such a way that it is capable of rotating about a pivot point or axis. The chamber includes three ports: a gas inlet port, a gas vent port, and a control volume port.

[0012] The pilot valve actuates the second stage (of the control valve), which is depicted illustratively as a bore in which a main-stage piston resides. It is the second stage, and in particular the position of the main-stage piston, which actually regulates the flow of gas propellant to the thrust nozzle.

[0013] The pilot valve pneumatically actuates the second stage by alternately pressurizing or depressurizing a control volume via the control volume port. In the illustrative embodiment, the control volume is the bore in which the main-stage piston resides. By way of additional detail, a small portion of gas is withdrawn from the main flow of gas propellant and is diverted to the gas inlet port of the chamber. In the illustrative embodiment, the pilot valve's rotor selectively pneumatically couples the control volume to either the gas inlet port or the gas vent port. When the control volume is coupled to the gas inlet port, the control volume is pressurized by the inlet gas. This forces the piston "upwards" in the bore into a blocking position in which it prevents access to the mouth of the thrust nozzle. On the other hand, when the control volume couples to the gas vent port, it depressurizes. Upon depressurization, the piston retracts within the bore into a non-blocking position with respect to the mouth of the thrust nozzle.

[0014] Unlike most prior art valves, the rotary-acting pilot valve described herein is configured and dimensioned so that the flow of gas is substantially perpendicular to the direction of rotation of the rotor and substantially parallel to its long axis. Due, at least in part, to this arrangement, a rotary-acting pilot valve in accordance with the illustrative embodiment is not required to lift against a pressure load, is substantially insensitive to g-loads and is relatively immune from pressure imbalances.

[0015] It is also notable that there is no contact between the rotor (*i.e.*, the valve element) and a seat surface. That is, a slight amount of leakage is permitted and expected. Another important aspect of a multi-stage valve that incorporates the rotary-acting pilot valve described herein is that, rather than controlling a large flow of gas, it controls a small flow of gas into and out of a control volume (*i.e.*, the cylinder). Consequently, the rotary-acting pilot valve requires a relatively small actuation force to move the rotor and, hence, consumes relatively little electromagnetic power.

[0016] These and other features of the illustrative embodiment of the present invention are described in detail in the following Detailed Description and depicted in the appended Drawings.

Brief Description of the Drawings

[0017] **FIG. 1A** depicts a conventional propulsion system including a hot-gas control valve, which is shown in a closed state.

[0018] **FIG. 1B** depicts the hot-gas control valve of FIG. 1A, wherein the valve is shown in an open state.

[0019] **FIG. 2A** depicts a propulsion system having a hot-gas control valve that incorporates a rotary-acting pilot valve in accordance with the illustrative embodiment of the present invention, wherein the control valve is shown in a closed state.

[0020] **FIG. 2B** depicts the hot-gas control valve that is shown in FIG. 2A in an open state.

[0021] **FIG. 3** depicts a chamber of the illustrative rotary-acting pilot valve.

[0022] **FIG. 4** depicts a top view of a rotor of the illustrative rotary-acting pilot valve.

[0023] **FIG. 5** depicts a side view of the rotor of FIG. 4.

[0024] **FIG. 6** depicts the illustrative rotary-acting pilot valve in a "pressurize" state in which it pneumatically couples a gas inlet port to the second stage of the hot-gas control valve of FIG. 2A.

[0025] **FIG. 7** depicts the illustrative rotary-acting pilot valve in a "depressurize" state in which it pneumatically couples the second stage to a gas vent port.

[0026] **FIG. 8** depicts the rotation angle of the rotor.

[0027] **FIG. 9** depicts the point of first contact between gas and the rotor, and illustrates that at this point of contact, the direction of rotation of the rotor is substantially perpendicular to the direction in which the gas flows.

[0028] **FIG. 10** depicts the rotary-acting pilot valve and highlights the relative radial locations (along the rotor) of the gas inlet port, control volume port, and gas vent port.

[0029] **FIG. 11** depicts a variation of the rotor that is shown in FIG. 4, wherein a passage is disposed at the end of the rotor nearest the gas inlet port.

Detailed Description

[0030] The illustrative embodiment of the present invention is a propulsion system that incorporates a rotary-acting valve. In the illustrative embodiment, the rotary-acting valve is used as the "pilot" or first stage of a two-stage, hot-gas control valve for controlling a flow of gas propellant to a thrust nozzle in a rocket or missile. The gas propellant, which in the illustrative embodiment is generated from a solid-fuel gas generator, is typically quite hot (*e.g.*, about 2500+ °F) and is at high pressure (*e.g.*, about 500 to 2000 psi).

[0031] It will be understood that the rotary-acting valve described herein can be used for other applications. For example, the rotary-acting pilot valve can be used in other services in a missile or rocket (*e.g.*, to control the flow of gas from solid-fuel gas generators to a secondary combustion chamber, *etc.*) and for non-aeronautical applications (*e.g.*, laboratory instrumentation, processing plants, *etc.*). Non-aeronautical applications will typically involve far less severe temperature and pressure environments, so that issues relating to materials selection and thermal design become less critical. It is within the capabilities of those skilled in the art to appropriately select materials and develop a thermal design consistent with the prevailing operating conditions.

[0032] FIGs. 2A and 2B depict propulsion system **200**, which incorporates hot-gas control valve ("HGCV") **208** in accordance with the illustrative embodiment of the present invention. In the illustrative embodiment, HGCV **208** regulates a flow of gas propellant **100** into thrust nozzle **102**. FIG. 2A depicts HGCV **208** in a "closed" state in which it prevents gas from flowing into mouth **104** of nozzle **102**. FIG. 2B depicts HGCV **208** in an "open" state. In the open state, HGCV **208** permits gas **100** to flow into mouth **104** of nozzle **102**.

[0033] HGCV **208** is a two-stage valve comprising "first-stage" or "pilot" valve **210** and "second-stage" valve **112**. Second-stage valve **112** controls the flow of gas **100** into mouth **104** of nozzle **102** while pilot valve **210** actuates or controls second-stage valve **112**. As described further below, pilot valve **210** actuates second-stage valve **112** by regulating the flow (into the second-stage valve, and

more particularly into a control volume) of a small portion of gas taken from the main flow of gas **100**.

[0034] With continued reference to FIGs. 2A and 2B, second-stage valve **112** comprises bore **116** and piston **114**. Bore **116** can have any suitable shape (*e.g.*, cylindrical, square, *etc.*) with piston **114** having a complementary shape. In some embodiments, the bore and piston can be keyed to prevent rotation.

[0035] Piston **114** piston moves linearly within bore **116** between a first position and a second position, as defined below. In the first position, which is depicted in FIG. 2A, piston **114** moves "upwards" in bore **116** into a blocking position in which it closes off mouth **104** of nozzle **102**. Doing so prevents gas **100** from entering the nozzle. In the second position, which is depicted in FIG. 2B, piston **114** moves "downwards," retracting into bore **116** into a non-blocking position. In this position, gas **100** in conduit **106** can enter nozzle **102**. As described further below, the position (first or second) of piston **114** depends upon the state of pilot valve **210**.

[0036] Referring now to FIGs. 2A through 7, pilot valve **210** comprises chamber **220** (FIG. 3, *etc.*) and rotor **228** (FIG. 4, *etc.*). The rotor resides within the chamber (FIGs. 2A, 2B, 6, and 7). In the illustrative embodiment, rotor **228** and chamber **220** have an elongated, hexagonal shape. The short sides of rotor **228** define a first end **230** and second end **232** (of rotor **228**).

[0037] Rotor **228** is supported within chamber **220** so that it is capable of rotating about axis or pivot point **1-1** (FIGs. 4, 5, *etc.*). In the illustrative embodiment, rotor **228** is supported by drive shaft **438**, which aligns with axis **1-1**. Drive shaft **438** couples rotor **228** to actuator **540** (FIG. 5). In the illustrative embodiment, actuator **540** is a stepper motor. In some other embodiments, different types of actuators and different actuating arrangements are used. For example, in some embodiments, rotor **228** is actuated by two pairs of solenoids (not depicted) that sandwich it — one pair at first end **230** and the second pair at second end **232**.

[0038] Chamber **220**, which houses rotor **228**, includes three ports: gas inlet port **222**, control volume port **224** to second stage **112**, and gas vent port **226**. With reference to FIGs. 2A and 2B, inlet port **222** pneumatically couples chamber **228** to conduit **106** via conduit **234**. For use in this specification, including the appended claims, the term **"pneumatically coupled"** means that the pressure or flow of gas/vapor in one region affects the pressure or flow conditions in another region. Typically, although not necessarily, pneumatically-coupled regions are physically

connected to one another by orifice(s) or conduit such that a continuous path from one region to the next is established.

[0039] Control volume port **224** pneumatically couples chamber **228** to second stage valve **112**, and, more particularly, to control volume **218** within bore **116**. For use in this specification, including the appended claims, the phrase "**control volume**" means a region between the bottom of piston **114** and the bottom of bore **116**. The size of the control volume varies as piston **114** moves within bore **116**. Vent port **226** physically couples chamber **228** to vent line **236**. The vent line is typically pneumatically coupled to a low-pressure region (*e.g.*, overboard from the missile to local atmospheric pressure, *etc.*).

[0040] Due in part to the physical relationships described above, rotor **228** is capable of performing the following functions: (1) pneumatically coupling gas inlet port **222** to control volume **218** and (2) pneumatically coupling control volume **218** to gas vent port **226**. By virtue of this functionality, pilot valve **210** controls the pressure in (*i.e.*, flow to) bore **116**. In response, control volume **218** alternatively either enlarges or contracts, moving piston **114** within bore **116**. In this way, pilot valve **110** actuates second stage valve **112**. This functionality is described further below.

[0041] FIGs. 2A and 6 depict pilot valve **210** in a "pressurize" state in which it performs function (1) — pneumatically coupling gas inlet port **222** to control volume **218**. In FIGs. 2A and 6, rotor **228** is positioned so that inlet port **222** is open (*i.e.*, not blocked by first end **230** of rotor **228**) while vent port **226** is closed (*i.e.*, blocked by second end **232** of rotor **228**).

[0042] When inlet port **222** is open, a small portion of gas (about 1 to 10 volume percent of the total amount of gas **100** in conduit **106**) flows from conduit **106** to conduit **234** and through inlet port **222** into chamber **220**. Once in chamber **220**, the gas flows past long side **642** of rotor **228**, through control volume port **224** and into control volume **218** within cylinder **116**. As gas **100** flows into control volume **218**, the control volume (*i.e.*, bore **116**) pressurizes, forcing piston **114** "upwards" until it contacts and seals mouth **104** of nozzle **102**. Thus, when pilot valve **210** is in the pressurize state (*i.e.*, gas inlet port **222** is open), control valve **208** closes, preventing gas propellant **100** from entering nozzle **102**.

[0043] FIGs. 2B and 7 depict pilot valve **210** in a "depressurize" state in which it performs function (2) — pneumatically coupling control volume **218** to vent port

226. In FIGs. 2B and 7, rotor **228** is positioned so that inlet port **222** is closed (*i.e.*, blocked by first end **230** of rotor **228**) while vent port **226** is open (*i.e.*, not blocked by second end **232** of rotor **228**). Consequently, gas flows from control volume **218** through outlet port **224**, past long side **744** of rotor **228**, through vent port **226** and into vent line **236**. As gas **100** flows out of control volume **218**, bore **116** depressurizes. This depressurization causes piston **114** to drop, thereby opening mouth **104** of nozzle **102**. As such, when pilot valve **210** is in the depressurize state (*i.e.*, gas inlet port **222** is closed), control valve **208** opens, permitting gas propellant **100** to enter nozzle **102**.

[0044] Rotor **228** and its operation are now described in further detail. To move between the two positions described above (*i.e.*, either blocking gas inlet port **222** or blocking vent port **226**), rotor **228** rotates or pivots about axis **1-1**. In some applications, it is desirable for pilot valve **210** to have a response time, τ, in the range of about 1 to 3 milliseconds. Consequently, rotation angle θ should be small, for example, in a range of about 3° to about 10° (*see* FIG. 8). Rotation of rotor **228** is, therefore, not a continuous rotation as in most rotary valves, but rather an oscillatory motion.

[0045] Unlike most valves, a slight amount of leakage is permitted and expected in pilot valve **210**. The leakage occurs since rotor **228** does not contact a "seat" when it blocks inlet port **222** or vent port **226**. To keep the leakage low, rotor **228** and chamber **220** should be manufactured with high precision so that there is a very small gap between end **230** of rotor **228** and gas inlet port **222** and end **232** of rotor **228** and gas vent port **226**. In some embodiments, the gap between an end of rotor **228** (*i.e.*, first end **230** and second end **232**) and the interior wall of chamber **220** near inlet and vent ports is about 0.0005 inches. Leakage in an amount of about 10 percent or less (volumetric flow) is readily achievable and will be acceptable in most cases. As previously disclosed, the amount of flow entering pilot valve **210** is quite small such that the actual amount of leakage is a very small quantity of gas.

[0046] Parameters such as the dimensions of rotor **228** and the flow area of inlet port **222** are primarily based on the desired response time, τ, and rotation angle θ. The torque required to actuate rotor **228** is calculated based on the rotor's angular acceleration and moment of inertia in known fashion. In some embodiments, rotor **228** includes open or "cut-out" regions **541** (FIG. 5). The cut-out regions reduce the

mass of rotor **228** and, hence, reduce the power required for actuation. Those skilled in the art will be able to design and construct illustrative pilot valve **210** in view of the present disclosure.

[0047] When pilot valve **210** is used as the first stage in a hot-gas control valve, particular attention must be paid to the thermal design of the pilot valve. In particular, the pilot valve must be able to withstand the high temperatures (about 2500 to 4000 °F) and high pressures (about 500 to 2000 psig) of the gas propellant. For such an application, the constituent components of pilot valve **210** (*e.g.*, rotor **228**, chamber **220**, *etc.*) are typically made from refractory metals, ceramics, carbon-carbon, or similar high-temperature materials. Additionally, a suitable pressure seal must be used on the rotor drive shaft (*i.e.*, drive shaft **438**). In some embodiments, graphite seal rings are used to seal the drive shaft.

[0048] Furthermore, the thermal expansion of rotor **228** and the inside wall of chamber **220** must be considered in view of the very small gap between those elements. In some embodiments, relative thermal expansion is controlled by fabricating rotor **228** and chamber **220** from the same material, thereby matching their thermal expansion coefficients. In some other embodiments, materials and configurations are appropriately selected, in known fashion, such that the combination of the thermal expansion coefficient(s) and thermal inertia maintains an approximately constant gap during operation. This is sometimes referred to as "thermal transient design." In yet some other embodiments, known thermal compensation mechanisms are incorporated into rotor **228**, chamber **220**, or both, to maintain an approximately constant gap over a range of temperatures.

[0049] By way of summary, illustrative pilot valve **210**, and multi-stage valves that incorporate it (*e.g.*, HGCV **208**, *etc.*) incorporate a number of distinctive features that provide a number of benefits. For example, illustrative pilot valve **210** incorporates the following features:

- Gas **100** flows toward or "into" pivot point **1-1**, substantially parallel to long axis **2-2** of rotor **228**, and substantially perpendicular to the direction of rotation (*see*, FIG. 9).
- Control volume port **224** is at a different "radius" or location ($\boldsymbol{R_0}$) along rotor **228** than inlet port **222** ($\boldsymbol{R_1}$) and vent port **226** ($\boldsymbol{R_2}$) (*see*, FIG. 10).

- Rather than controlling a large flow of gas in conduit **106**, pilot valve **210** controls the flow of a small amount of gas into and out of a control volume (*i.e.*, control volume **218**).
- There is no contact between rotor **228** and a seat surface.

As a consequence of these and other features, some embodiments of pilot valve **210** and multi-stage valves that incorporate it offer at least some of the following advantages:

- They do not lift against a pressure load.
- They are substantially insensitive to g-loads.
- They are immune from pressure imbalances.
- They require little actuation force (hence low electromagnetic power consumption).
- They have pneumatically-assisted actuation.
- They exhibit a slight amount of leakage, which is not problematic and is, in fact, expected.

[0050] FIG. 11 depicts a variation of rotor **228** wherein the structure of the rotor itself facilitates pneumatically-assisted actuation. In particular, rotor **228** includes passage **1146**. The passage conducts a small amount of gas **100** to the region "above" end **230** of rotor **228**, whose flow generates a small thrust, and hence torque on rotor **228**. The gas flow assists actuator **540** in rotating rotor **228** "downward" to open inlet port **222**.

[0051] It is to be understood that the above-described embodiments are merely illustrative of the present invention and that many variations of the above-described embodiments can be devised by those skilled in the art without departing from the scope of the invention. For example, in some variations of the illustrative embodiment, the rotary-acting valve functions as a single-stage valve for any of a variety of services. And in some other variations of the illustrative embodiment, the rotary-acting valve serves as the first stage of a valve having more than two stages. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.